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MECHANICAL RESPONSE OF POST-TREATED WOVEN FLAX EPOXY LAMINATES UNDER LOW-VELOCITY IMPACT AND QUASI-STATIC INDENTATION.

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ABSTRACT:
This study investigates the synergistic effects of alkali post-treatment and fiber orientation on the impact behavior of woven flax fiber-reinforced epoxy laminates. Six distinct layup configurations—were fabricated using the hand layup technique. Post-curing, the laminates were chemically treated with 5% and 10% sodium hydroxide (NaOH) to enhance fiber–matrix interfacial bonding. Mechanical performance under impact loading was assessed through drop weight (low-velocity impact) and quasi-static indentation (QSI) tests at impact energies of 5 J, 10 J, and 15 J. The 5% NaOH-treated composites exhibited superior energy absorption across all layups, with maximum QSI absorption efficiency reaching 78.7% in symmetric hybrid (D) and 78.6% in group hybrid (E) configurations at 15 J. Angle-ply (F) and hybrid stacking (C) configurations also demonstrated comparable resistance (78.3%–78.4%). These improvements were attributed to enhanced fiber–matrix adhesion and favorable in-plane load distribution enabled by the multi-angled orientations. In contrast, the 10% NaOH treatment, while improving bonding, led to marginal fiber degradation, slightly reducing energy absorption efficiency (typically 75.7%–75.9%). Unidirectional stacks (A) consistently showed the lowest performance due to directional stress concentration and limited delamination control. The results underscore the importance of optimizing both chemical surface modification and laminate architecture to achieve high-impact resistance in natural fiber composites. This study provides a pathway for developing sustainable, lightweight, and structurally resilient materials for automotive and aerospace applications where energy absorption and eco-efficiency are critical.

Keywords: alkali treatment, Hand layup technique, flax fiber, epoxy resin composite.

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1. INTRODUCTION

Natural fiber composites (NFCs) have garnered significant attention in various industries, including automotive, aerospace, and construction, as sustainable and lightweight alternatives to synthetic fiber composites. Among the diverse natural fibers available, flax fibers stand out due to their excellent specific mechanical properties, renewability, biodegradability, and relatively low cost. These attributes make flax fiber-reinforced polymer composites a promising material for environmentally conscious applications. Despite their advantages, natural fibers often suffer from inherent limitations that can hinder the overall performance of their composites. A primary concern is the poor interfacial adhesion between the hydrophilic natural fibers and hydrophobic polymer matrices. This incompatibility arises from the presence of hydroxyl groups on the fiber surface, leading to weak bonding and inefficient stress transfer at the fiber-matrix interface. Consequently, NFCs can exhibit reduced mechanical properties, particularly under dynamic loading conditions. To address this challenge, alkali treatment, also known as mercerization, has emerged as a widely adopted chemical modification technique for natural fibers. This treatment involves immersing laminated composites in an alkaline solution (e.g., sodium hydroxide, NaOH), which removes hemicellulose, lignin, and pectin, and roughens the fiber surface. While the influence of alkali treatment on the static mechanical properties of flax fiber composites has been extensively studied, their behavior under dynamic loading conditions, specifically low-velocity impact and indentation, remains an area requiring further comprehensive investigation. Low-velocity impact events, such as tool drops or minor collisions, are common in real-world applications and can cause significant damage, often in the form of delamination or matrix cracking, without immediate visual cues. Quasi static Indentation, on the other hand, provides insights into the material's resistance to localized deformation and penetration, which is crucial for applications requiring surface durability. Understanding the response of alkali-treated woven flax epoxy composites to these specific loading scenarios is critical for their reliable design and implementation in structural applications.

2. LITERATURE REVIEW

Lukmon Owolabi Afolabi et al. [1] analyses carried out on each of the treated fiber have considerable effect on the extraction, chemical concentration and soaking time. Higher cellulose percentage can be obtained by increasing the chemical concentration and soaking time, however,fiber roughening and separation of the elementary fiber are the observed set-back . Mukesh et al. [2], The effect of different chemical modification of fiber surface on different mechanical properties of natural fibers composites are reviewed in this paper. Different fiber surface modifications like alkali, acetylation, potassium permanganate, peroxides, silane benzoylation etc. and the composition of the natural fibers components like cellulose, hemi-cellulose, lignin, pectin etc. are discussed. H. A. Aisyah et al. [3], analyzed that thermal stability of the pure carbon fibre composite was higher than that of the hybrid composite, the thermal stability of the hybrid composites improved as higher content of kenaf fibre was used, i.e., fabric density of 6 × 6. It was found that using the plain weave design of woven kenaf has improved the overall thermal stability of the samples compared to that of the satin design Senthil Ganesh Subramanian et al. [4], conclude that the unexploited C. Hildmannianus endow structural fiber or fiber bundle new hope for bio-composite industries with their precise following properties Sureshkumar Perumal Singaraj et al. [5], attempted to assess three types of banana fabrics for physical, morphological and thermal properties and to ascertain whether they can be combined with leathers to make combination products. It was found that most of the physical properties of banana fabrics are better than that of buffalo shrunken grain leather and, in some cases, it is even

comparable. Amirhossein Lotfi et al. [6], investigated the main challenges associated with machining of NFRCs and the induced damages are outlined, with special attention paid to the effect of physical properties of the fibers and manufacturing process on the machinability, along with the essential machining parameters that affect the quality of the machined surface Shaoquan et al. [7] studied the C/BMI (Carbon/Bismaleimide) composite's low-velocity impact behavior during supersonic hygrothermal flight cycles. The BMI composite's oxidation and degradation brought on by hygrothermal cycles, along with the interfacial debonding in the fibre and matrix, are likely to have contributed to the matrix's softening, which in turn reduced stiffness N Ramli et al. [8], investigated on bio-composite which is suitable to replace the existing interior of automotive design, the work has focused on obtaining that bio-composite, taking account into the raw-materials cost reduction and the maintenance of the manufacturing process based on current scenario. Miklos Tisza et al. [9], In this paper, an introduction on recent material developments in the automotive industry concerning both the use of new generation high strength steels and light metals with particular emphasis on aluminium alloys will be given. A comparison between steel and aluminium application in the automotive industry is given from various points of view. Subhakanta Nayak et al. [10], using treated Areca sheath (AS) fiber in polyvinyl chloride (PVC) matrix by injection molding method shows that AS/PVC composite can be appropriate substitute material for production of automobile dashboard panel. Susilendra Mutalikdesai et al. [11], use of the natural fibers offers the potential to act as a reinforcing material for composites alternative to the use of glass fiber, carbon fiber and other man-made fibers. In present work hybrid composites of Epoxy/basalt fiber/flax fibers were prepared by Hand-layup technique Heow Pueh Lee et al. [12], investigated the sound absorption properties of flax/epoxy composites and found them to be superior to those of glass/epoxy composites. A noteworthy result was that the noise reduction coefficient increased from an average value of 0.095–0.11 for unidirectional flax/ epoxy composite and to 0.10 for cross-ply flax/epoxy system. Bambach et.al [13] presents the compressive properties of plate and channel sections made of flax reinforced epoxy laminates and different plate thicknesses are compared. It is shown that even if the mechanical properties of the laminates are low, the buckling and post buckling response is stable and therefore suitable for light structural applications for the thicker specimens. Hawa et al. [14] investigated the burst strength and impact behavior of hygrothermal aged E-glass fibre/epoxy composite pipes. To conduct the ageing process specimens were placed in tap water for 500, 1000 and 1500 h. and maintained at 80°C. Upon impact loading, the peak force was largest for the unaged specimen, and it gradually decreased as ageing duration increased Bledzki, A. K. et al [15] Alkali treatment has been shown to significantly improve the tensile strength of flax fiber composites. This enhancement is attributed to the improved fiber-matrix adhesion and the increased cellulose content after treatment. Zhou, F., & Zhang, X [16] Flax fiber composites treated with NaOH exhibit higher flexural strength compared to untreated fibers, as the treatment enhances fiber bonding with the matrix, leading to better stress transfer

3. METHODOLOGY

In this study the Composite laminates were fabricated using woven flax fabric and epoxy resin via the hand layup technique. A clean mold surface was coated with a release agent, and pre-cut flax layers were stacked in angle-ply and cross-ply orientations. An epoxy-hardener mixture (10:1 ratio) was applied to maintain a 40:60 fiber-to-resin weight ratio for optimal impregnation. Resin was brushed between layers, and manual rolling ensured air removal and laminate compaction. The layup was cured at room temperature under pressure, followed by ambient post-curing before demolding. After fabrication, cured laminates were post-treated by immersion in 5% and 10% NaOH solutions to evaluate the effect of alkaline exposure on fiber–matrix interaction and surface properties. The influence of ply orientation was also examined by

comparing the mechanical performance of treated and untreated laminates across various layup configurations.

Figure 1: Hand layup process and final specimen

3.1 Materials

- Woven flax fabrics: The material were sourced from a reliable supplier and used in their raw form without any pretreatment for the control group. The flax fabric was carefully cleaned to remove any debris or loose fibers before use.
- Epoxy Resin: A commercial-grade epoxy resin system was used as the matrix material. The resin was mixed according to the manufacturer's instructions, ensuring proper curing and optimal bonding.
- Sodium Hydroxide (NaOH): Two concentrations of NaOH (5% and 10%) were prepared by dissolving the appropriate amount of NaOH pellets in distilled water. These solutions were used for the alkali treatment of the flax fibers.

3.2 Selection of Material

Flax comes from the stem of the flax plant of the species Linum usitatissimum. Flax fibre is classified as a natural cellulose, bast and multicellular fibre. When the fibre is processed into fabric, then it is called as Lenin.

It is one of the strongest fibres, and it is considered for their strength, durability, and absorbency, as well as their unique texture. In addition to its traditional uses, flax fibre is becoming increasingly popular in modern times as a sustainable alternative to synthetic fibres. and the chemical composition is as shown below Table.1

Table 1: Structural composition of Flax fibre

Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Pectins (wt%)	Micro fibril angle (degree)	Moisture content (wt%)
71	18.6–20.6	2.2	2.3	6-7	10

3.3 Layup – Orientations

The mechanical behaviour of composite laminates is heavily influenced by their layup orientation, i.e., the sequence and angular alignment of fiber layers within the laminate. Each ply orientation contributes differently to the overall stiffness, strength, and damage resistance of the composite, especially under complex loading conditions such as impact or indentation.

Table 2: Different Layup configurations

Sample	Layup Configuration	Description
A	Unidirectional stack	All plies oriented the same (warp 0°, weft 90°)
B	±45° rotation	Woven layers rotated ±45° alternately
C	Hybrid stacking	Alternate 0°/90°0°/90° and ±45°±45° rotated fabric
D	Symmetric hybrid	Balanced layout with mirrored stacking
E	Grouped hybrid	8 plies 0°/90°0°/90° + 8 plies ±45°±45°
F	Angle ply	Woven fabric rotated at ±30° and ±60°

3.4 Water Absorption

Water absorption tests of the developed composites were conducted as per ASTM D570 by immersion in distilled water along with 5% of NAOH and 10% NAOH at room temperature for a long time period to reach a stable equilibrium or saturation point.

Figure 2: Treated specimen for water absorption

The samples were taken out after each time interval and water particles are wiped out from the surface of the specimen using filter paper. Samples are weighed immediately within 30 s to avoid error due to evaporation, using an electronic balance (AY220 type, ±0.1 mg accuracy). After weighing, the sample is immersed in the water bath to permit water absorption until the saturation point is reached after 30-45 Days. The weight difference of the specimen gives the value of the water absorption. The water content percentage (Mt), is calculated using Eq (1).

$$M_t(\%) = \frac{W_t - W_o}{W_o} \times 100 \quad \ldots\ldots\ldots\

Table 3: Maximum water absorption of Woven flax fabric Epoxy composite at 5 % NaOH

Time (hours)	Weight Gain (%)					
	Sample A	**Sample B**	**Sample C**	**Sample D**	**Sample E**	**Sample F**
0	0	0	0	0	0	0
24	0.35	0.47	0.43	0.56	0.68	0.78
48	0.68	0.90	0.83	1.08	1.30	1.51
72	0.98	1.30	1.19	1.56	1.88	2.18
96	1.26	1.67	1.53	2.00	2.41	2.79
120	1.52	2.01	1.85	2.41	2.90	3.36
144	1.75	2.33	2.13	2.78	3.35	3.89
168	1.97	2.62	2.40	3.13	3.77	4.37
192	2.17	2.88	2.65	3.45	4.16	4.82
216	2.36	3.13	2.87	3.75	4.52	5.24
240	2.53	3.36	3.08	4.02	4.85	5.62
264	2.69	3.57	3.28	4.27	5.15	5.97
288	2.84	3.76	3.46	4.50	5.43	6.29
312	2.97	3.94	3.62	4.72	5.69	6.59
336	3.10	4.11	3.77	4.92	5.93	6.87
360	3.21	4.26	3.91	5.10	6.15	7.13
384	3.32	4.40	4.04	5.27	6.35	7.36
408	3.42	4.53	4.16	5.43	6.54	7.58
432	3.51	4.65	4.27	5.57	6.72	7.78
456	3.59	4.77	4.38	5.70	6.88	7.97
480	3.67	4.87	4.47	5.83	7.02	8.14
504	3.74	4.96	4.56	5.94	7.16	8.30
528	3.81	5.05	4.64	6.04	7.29	8.45
552	3.87	5.13	4.71	6.14	7.40	8.58
576	3.93	5.21	4.78	6.23	7.51	8.70
600	3.98	5.27	4.84	6.31	7.61	8.82
624	4.03	5.34	4.90	6.39	7.70	8.93
648	4.07	5.40	4.95	6.46	7.79	9.02
672	4.11	5.45	5.00	6.52	7.86	9.11
696	4.15	5.50	5.05	6.58	7.94	9.20
720	4.00	5.50	5.05	6.00	7.00	9.00
744	4.00	5.50	5.05	6.00	7.00	9.00
768	4.00	5.50	5.05	6.00	7.00	9.00
792	4.00	5.50	5.05	6.00	7.00	9.00
816	4.00	5.50	5.05	6.00	7.00	9.00
840	4.00	5.50	5.05	6.00	7.00	9.00
864	4.00	5.50	5.05	6.00	7.00	9.00
888	4.00	5.50	5.05	6.00	7.00	9.00
912	4.00	5.50	5.05	6.00	7.00	9.00
936	4.00	5.50	5.05	6.00	7.00	9.00
960	4.00	5.50	5.05	6.00	7.00	9.00

Table 4: Maximum water absorption of Woven flax fabric Epoxy composite at 10 % NaOH

Time (hours)	Weight Gain (%)					
	Sample A	**Sample B**	**Sample C**	**Sample D**	**Sample E**	**Sample F**
0	0	0	0	0	0	0
24	0.52	0.60	0.84	0.72	0.77	0.75
48	0.99	1.15	1.61	1.39	1.48	1.45
72	1.43	1.66	2.31	2.01	2.13	2.09
96	1.83	2.14	2.99	2.57	2.74	2.68
120	2.21	2.57	3.58	3.10	3.30	3.23
144	2.55	2.97	4.13	3.58	3.81	3.74
168	2.87	3.34	4.66	4.03	4.29	4.20
192	3.17	3.69	5.15	4.44	4.73	4.63
216	3.44	4.00	5.58	4.82	5.13	5.03
240	3.69	4.30	6.00	5.18	5.51	5.40
264	3.92	4.56	6.37	5.50	5.85	5.74
288	4.13	4.81	6.71	5.80	6.17	6.05
312	4.33	5.04	6.71	6.08	6.47	6.34
336	4.51	5.26	6.71	6.33	6.74	6.60
360	4.68	5.45	6.71	6.57	6.99	6.85
384	4.84	5.63	6.71	6.79	7.22	7.08
408	4.98	5.80	6.71	6.99	7.43	7.28
432	5.11	5.95	6.71	7.17	7.63	7.48
456	5.23	6.09	6.71	7.34	7.81	7.66
480	5.35	6.23	6.71	7.50	7.98	7.82
504	5.45	6.35	6.71	7.65	8.14	7.97
528	5.55	6.46	6.71	7.78	8.28	8.11
552	5.64	6.56	6.71	7.91	8.41	8.24
576	5.72	6.66	6.71	8.02	8.53	8.36
600	5.79	6.74	6.71	8.13	8.65	8.47
624	5.86	6.83	6.71	8.23	8.75	8.58
648	5.93	6.90	7.50	8.32	8.75	8.67
672	5.99	6.97	7.50	8.40	8.76	8.76
696	6.04	7.03	7.50	8.40	8.76	8.84
720	6.00	7.00	7.50	8.40	8.76	9.00
744	6.00	7.00	7.50	8.40	8.76	9.00
768	6.00	7.00	7.50	8.40	8.76	9.00
792	6.00	7.00	7.50	8.40	8.76	9.00
816	6.00	7.00	7.50	8.40	8.76	9.00
840	6.00	7.00	7.50	8.40	8.76	9.00
864	6.00	7.00	7.50	8.40	8.76	9.00
888	6.00	7.00	7.50	8.40	8.76	9.00
912	6.00	7.00	7.50	8.40	8.76	9.00
936	6.00	7.00	7.50	8.40	8.76	9.00
960	6.00	7.00	7.50	8.40	8.76	9.00
984	6.00	7.00	7.50	8.40	8.76	9.00

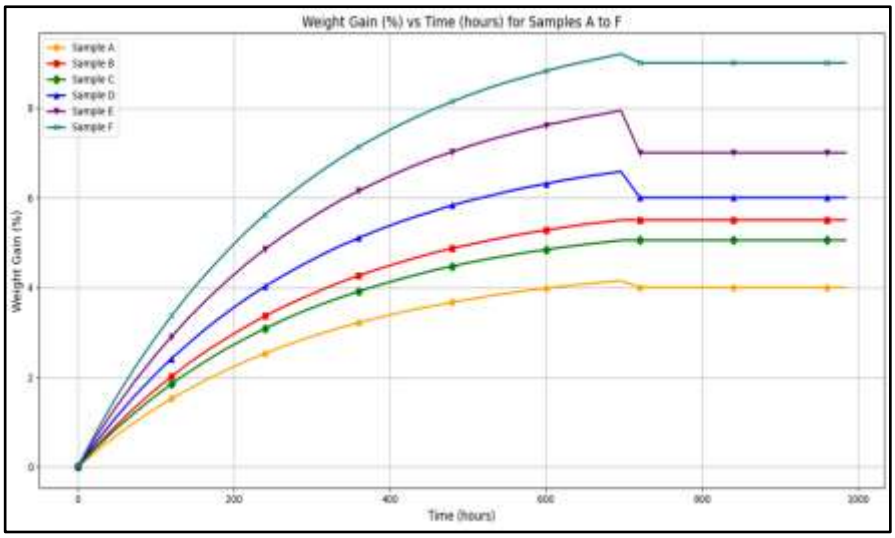

Figure 3: Water absorption behaviour for sample A-F at 5% NaOH

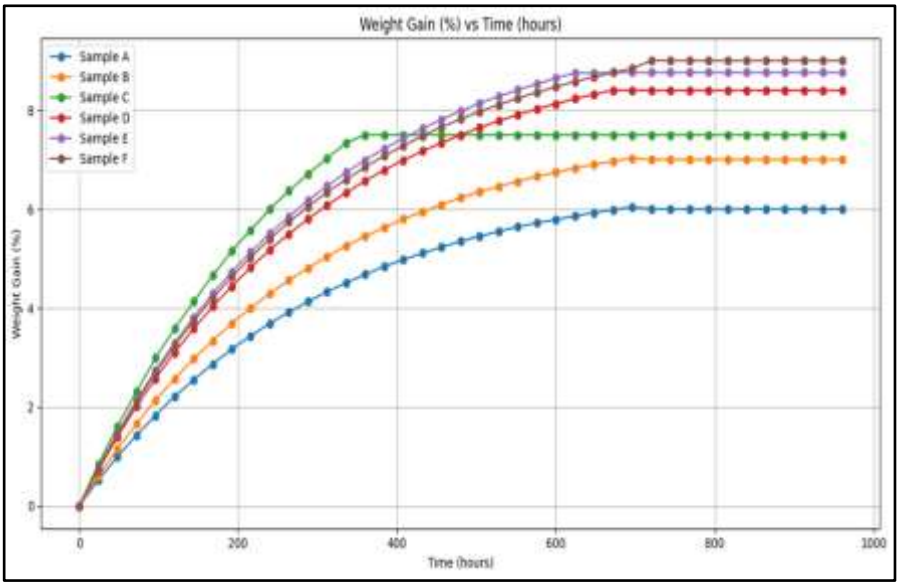

Figure 4: Water absorption behaviour for sample A to F at 10% NAOH

3.4 Quasi static Indentation (QSI)

The quasi-static (QS) indentation tests were based on the standards ASTM D7136/D7136M−15 and ASTM D 6264−12. The rig comprises three main components: a sturdy steel frame, a hydraulic system, and a data acquisition and control system The load cell used had a maximum capacity of 10 kN and the displacement was measured with a 150 mm linear potentiometer. The Quasi static Indentation (QSI) test will be performed with a constant velocity applied to the indenter. In this study a test speed of 0.25 mm/s was used for the QSI tests. The velocity selected for the present study was 0.5 mm/s, as no dynamic effects were observed, and the test duration could be reduced to around 1 min.

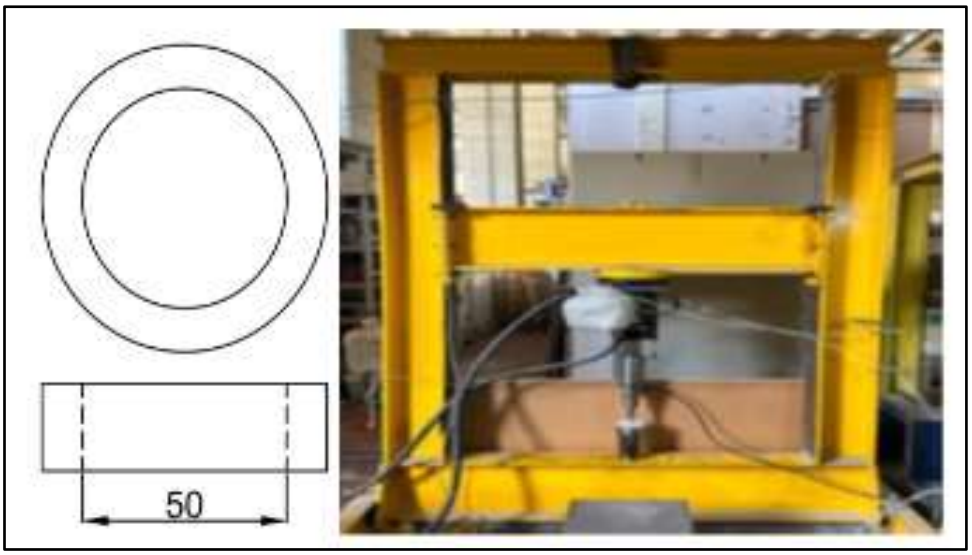

Figure 5: shows Quasi-static (QS) indentation specimen and Test Rig

During the study there were several key parameters can be compared from each test stage. The first was related to the absorbed energy at defined perforation. Other parameters were also found significant, like the load measured and absorbed energy at maximum load, initial fibre failure and initial matrix damage.

3.5 Low-velocity impact

The low-velocity impact tests were based on the standard ASTM D7136/D7136M−15. For the impact tests, A drop weight machine was utilized, displayed in Figure 6. To enable the comparison between the results of the QS indentation test and the low-velocity impact test, identical test setups were employed (i.e., same specimen dimensions, support system and indenter).

Figure 6: Low velocity Impact testing machine

4. RESULTS AND DISCUSSIONS

The results presents the influence of alkali post-treatment and fiber lay-up orientation on the mechanical performance of woven flax/epoxy laminates. Variations in impact energy absorption, stiffness, and failure modes were analyzed across untreated, 5% NaOH, and 10% NaOH treated samples. Different lay-up configurations were evaluated to assess their role in distributing impact loads and enhancing structural integrity. The findings highlight key trends in treatment effectiveness and orientation-dependent behaviour.

4.1 Results of Quasi- Static Test (QSI)

Quasi-Static Indentation (QSI) tests were conducted to evaluate the resistance of the composite laminates with a hemispherical impactor at energies of 5, 10, and 15J. to localized penetration under gradually applied loads. This method provides insights into damage mechanisms such as matrix

cracking, delamination, and fiber–matrix debonding under compressive contact conditions. The results of quasistatic indentation are mentioned in below Table 5.

Table 5: Results of Quasistatic indentation Test for treated and Untreated Samples A -F

Sample	Impact	Untreated Et (J)	Ea (J)	Ea/Et (%)	5% NaOH Et (J)	Ea (J)	Ea/Et (%)	10% NaOH Et (J)	Ea (J)	Ea/Et (%)
A	5 J	5.00 ± 0.19	2.60 ± 0.14	52	5.11 ± 0.18	3.21 ± 0.16	62.8	5.03 ± 0.22	2.88 ± 0.17	57.3
	10 J	9.00 ± 0.08	5.60 ± 0.06	62.2	9.17 ± 0.05	6.36 ± 0.05	69.4	9.01 ± 0.08	6.01 ± 0.07	66.7
	15 J	15.75 ± 0.22	11.01 ± 0.17	69.9	15.99 ± 0.24	12.59 ± 0.16	78.5	15.82 ± 0.26	12.01 ± 0.18	75.9
B	5 J	4.95 ± 0.21	2.57 ± 0.13	51.9	5.05 ± 0.20	3.15 ± 0.15	62.4	5.00 ± 0.20	2.85 ± 0.15	57
	10 J	8.98 ± 0.10	5.59 ± 0.07	62.3	9.12 ± 0.10	6.30 ± 0.07	69.1	8.98 ± 0.09	5.98 ± 0.08	66.6
	15 J	15.70 ± 0.23	10.99 ± 0.19	70	15.90 ± 0.25	12.45 ± 0.20	78.3	15.78 ± 0.25	11.96 ± 0.21	75.8
C	5 J	4.97 ± 0.20	2.58 ± 0.12	51.9	5.08 ± 0.17	3.18 ± 0.14	62.6	5.01 ± 0.19	2.86 ± 0.16	57.1
	10 J	9.00 ± 0.09	5.60 ± 0.07	62.2	9.15 ± 0.08	6.34 ± 0.06	69.3	9.00 ± 0.07	5.99 ± 0.07	66.6
	15 J	15.72 ± 0.24	11.00 ± 0.18	70	15.95 ± 0.23	12.50 ± 0.18	78.4	15.80 ± 0.24	11.98 ± 0.20	75.8
D	5 J	5.01 ± 0.18	2.60 ± 0.11	51.9	5.13 ± 0.15	3.22 ± 0.12	62.7	5.05 ± 0.18	2.87 ± 0.14	56.8
	10 J	9.02 ± 0.07	5.61 ± 0.06	62.2	9.18 ± 0.06	6.38 ± 0.05	69.5	9.03 ± 0.06	6.02 ± 0.06	66.7
	15 J	15.78 ± 0.22	11.03 ± 0.16	69.9	16.00 ± 0.20	12.60 ± 0.17	78.7	15.85 ± 0.23	12.00 ± 0.17	75.7
E	5 J	4.99 ± 0.19	2.59 ± 0.13	51.9	5.10 ± 0.19	3.20 ± 0.13	62.7	5.02 ± 0.20	2.86 ± 0.15	57
	10 J	9.00 ± 0.08	5.60 ± 0.06	62.2	9.16 ± 0.07	6.35 ± 0.06	69.3	9.00 ± 0.07	5.99 ± 0.06	66.6
	15 J	15.73 ± 0.23	11.00 ± 0.18	70	15.97 ± 0.21	12.57 ± 0.18	78.6	15.81 ± 0.25	11.97 ± 0.19	75.7

F	5 J	4.93 ± 0.22	2.55 ± 0.14	51.7	5.02 ± 0.21	3.12 ± 0.16	62.1	4.98 ± 0.22	2.83 ± 0.16	56.8
	10 J	8.96 ± 0.09	5.58 ± 0.07	62.3	9.10 ± 0.09	6.28 ± 0.08	69	8.97 ± 0.08	5.97 ± 0.07	66.5
	15 J	15.69 ± 0.25	10.98 ± 0.20	70	15.85 ± 0.26	12.42 ± 0.22	78.3	15.76 ± 0.27	11.94 ± 0.22	75.7

Discussions: The quasi-static indentation tests revealed clear trends in energy absorption behavior influenced by both alkali post-treatment and layup orientation. For all specimens (A–F), 5% NaOH post-treated laminates consistently demonstrated the highest energy absorption efficiencies, with values reaching 78.3% to 78.7% at 15 J impact. In contrast, untreated specimens exhibited lower absorption, ranging between 69.9% and 70%, while 10% NaOH-treated samples showed marginally reduced efficiencies (75.7%–75.9%) compared to the 5% group, likely due to fiber degradation at higher alkali concentrations. Among orientations, configurations D (symmetric hybrid), E (group hybrid), and C (hybrid stacking) displayed the most significant improvements post-treatment, indicating that multi-directional fiber architectures promote better stress distribution and damage tolerance.

4.2 Results of Low velocity Impact Test (LVI)

The low-velocity impact test assessed the energy absorption and damage tolerance of flax fiber laminates under sudden loading conditions. Samples A–F were impacted at 5 J, 10 J, and 15 J energies to evaluate load-bearing response and failure modes. The test results for untreated and treated for different samples are in below Table 6.

Table 6: Low velocity Impact test Sample Results A to F

Sample	**Impact (J)**	**Untreated Et (J)**	**Ea (J)**	**Ea/Et (%)**	**5% NaOH Et (J)**	**Ea (J)**	**Ea/Et (%)**	**10% NaOH Et (J)**	**Ea (J)**	**Ea/Et (%)**
A	5	5.32 ± 0.24	3.71 ± 0.21	69.7	5.11 ± 0.18	3.21 ± 0.16	62.8	4.92 ± 0.22	3.08 ± 0.19	62.6
	10	9.60 ± 0.20	7.12 ± 0.28	74.2	9.17 ± 0.05	6.36 ± 0.05	69.4	8.97 ± 1.16	5.80 ± 0.39	64.7
	15	16.20 ± 0.36	13.10 ± 0.41	80.9	15.99 ± 0.24	12.55 ± 0.16	78.5	15.76 ± 0.73	10.71 ± 0.51	68
B	5	5.25 ± 0.21	3.65 ± 0.22	69.5	5.08 ± 0.19	3.24 ± 0.18	63.8	5.05 ± 0.18	3.22 ± 0.20	63.8
	10	9.45 ± 0.18	6.95 ± 0.31	73.5	9.20 ± 0.09	6.40 ± 0.27	69.6	9.11 ± 0.72	6.01 ± 0.36	66
	15	16.10 ± 0.27	12.42 ± 0.46	77.2	15.88 ± 0.35	12.11 ± 0.37	76.3	15.82 ± 0.80	11.00 ± 0.54	69.5
C	5	5.18 ± 0.26	3.58 ± 0.25	69.1	5.00 ± 0.22	3.05 ± 0.17	61	4.88 ± 0.26	2.91 ± 0.22	59.6
	10	9.30 ± 0.22	6.70 ± 0.28	72	9.12 ± 0.11	6.32 ± 0.30	69.3	8.75 ± 0.69	5.60 ± 0.34	64
	15	15.95 ± 0.29	12.31 ± 0.49	77.2	15.90 ± 0.33	12.29 ± 0.45	77.3	15.63 ± 0.69	10.55 ± 0.50	67.5

D	5	5.29 ± 0.23	3.66 ± 0.20	69.2	5.08 ± 0.19	3.22 ± 0.17	63.4	5.03 ± 0.17	3.14 ± 0.18	62.4
	10	9.48 ± 0.25	6.78 ± 0.30	71.5	9.15 ± 0.08	6.30 ± 0.29	68.9	9.03 ± 0.85	5.88 ± 0.42	65.1
	15	16.05 ± 0.35	12.10 ± 0.52	75.4	15.92 ± 0.32	12.25 ± 0.46	77	15.90 ± 0.74	10.92 ± 0.53	68.7
E	5	5.22 ± 0.20	3.63 ± 0.19	69.5	5.03 ± 0.21	3.13 ± 0.16	62.2	5.00 ± 0.20	3.11 ± 0.17	62.2
	10	9.20 ± 0.24	6.62 ± 0.32	71.9	9.00 ± 0.10	6.25 ± 0.28	69.4	8.88 ± 0.93	5.75 ± 0.40	64.7
	15	15.88 ± 0.30	12.08 ± 0.50	76.1	15.80 ± 0.31	12.00 ± 0.44	75.9	15.79 ± 0.68	10.83 ± 0.48	68.6
F	5	5.20 ± 0.25	3.58 ± 0.22	68.8	5.01 ± 0.20	3.06 ± 0.18	61.1	4.95 ± 0.24	3.05 ± 0.21	61.6
	10	9.25 ± 0.27	6.58 ± 0.35	71.1	9.10 ± 0.12	6.20 ± 0.29	68.1	9.05 ± 0.78	5.92 ± 0.38	65.4
	15	16.00 ± 0.38	12.20 ± 0.46	76.3	15.86 ± 0.29	12.08 ± 0.42	76.1	15.85 ± 0.70	10.96 ± 0.52	69.2

Discussions:

- The experimental results reveal a clear dependency of energy absorption behavior on both impact energy and post-treatment conditioning. Across all specimens, a progressive increase in absorbed energy (Ea) and absorption efficiency (Ea/Et %) is observed with increasing impact levels (5 J to 15 J), indicating enhanced damage tolerance under higher loading. Notably, laminates subjected to 5% NaOH post-treatment exhibit superior energy absorption characteristics, suggesting effective fiber-matrix interfacial modification that promotes improved stress transfer and localized energy dissipation during impact. In contrast, 10% NaOH treatment, while initially beneficial at lower energies, results in reduced performance at 15 J, potentially due to over-etching of flax fibers, leading to partial loss of structural integrity and diminished load-bearing capacity. This trend underscores the criticality of optimizing chemical conditioning parameters to avoid compromising fiber morphology. Additionally, the variation in energy absorption across layup configurations highlights the role of fibre orientation and stacking sequence in influencing damage evolution, delamination resistance, and overall impact mitigation in natural fibre composites.

5. CONCLUSIONS

This study examined the effect of alkali treatment using 5% and 10% NaOH solutions on the load-bearing capacity of woven flax epoxy composites. The mechanical performance of these composites was evaluated using quasi-static indentation, and low-velocity impact tests. The main findings and conclusions are as follows:

- 5% NaOH post-treatment significantly enhanced impact energy absorption, achieving up to ~80.9% absorption efficiency at 15 J, outperforming both untreated and 10% NaOH-treated laminates.

- 10% NaOH-treated laminates showed diminished performance at higher energy levels, likely due to microstructural degradation of flax fibers, confirming that overtreatment compromises composite toughness.
- The increase in impact energy led to proportionally higher energy absorption, indicating good strain tolerance and stable energy dissipation characteristics of woven flax laminates under dynamic loading.
- Untreated laminates consistently exhibited lower absorption efficiency (typically <70%), underscoring the importance of fiber–matrix interfacial enhancement through post-treatment.
- Variation in ply orientation influenced load distribution, but 5% NaOH treatment remained effective across all layups, confirming its robustness for diverse laminate architectures

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